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Risk-Based Maintenance Scheduling with application to naval vessels and ships

Jane Cullum [a,*], Jonathan Binns [a], Michael Lonsdale [b], Rouzbeh Abbassi [a], Vikram Garaniya [a]

[a] Australian Maritime College, University of Tasmania, Maritime Way, Newnham 7248, Tasmania, Australia
[b] Serco Defence Asia-Pacific, 60 Margaret Street, Sydney 2000, New South Wales, Australia

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ABSTRACT

Maintenance scheduling for naval vessels and ships requires ongoing improvement to manage rising maintenance costs within availability constraints. Existing maintenance scheduling approaches are not optimal as maintenance costs continue to rise without an improvement in vessel availability. This paper reviews the Risk-Based Maintenance Scheduling (RBM) framework as applied to ships and naval vessels, and provides a critical analysis of Risk Assessment and Maintenance Scheduling techniques used. Further, objectives and considerations are defined for future applications for ships and naval vessels, and the framework evaluated as an improvement on existing Preventative Maintenance (PM) and Reliability Centered Maintenance (RCM) methods. A probabilistic approach supported by condition monitoring data in combination with Decision Theory is suggested for the Risk Assessment and Maintenance Scheduling elements comprising an RBM Scheduling framework. Implementation of this framework from both periodic PM and RCM is presented. Development of applications from the component level upwards is suggested. Availability and overall maintenance cost are suggested as evaluation metrics against existing methods. The development of an application is formalized within a proposed framework. The development of an application within the RBM Scheduling framework is expected to result in reduced maintenance costs while meeting availability requirements for ship and naval vessel applications.

1. Introduction

A reduction in equipment availability aboard naval vessels due to failure or maintenance is undesirable. Failures due to ineffective maintenance have undoubtedly occurred in naval applications, though detailed reports of these events are not publicly available.

Availability and reliability requirements are met through significant investment in maintenance for these complex vessels (Eruguz et al., 2015). Button et al. (2015) had shown that for the US Navy the required investment was approximately 22 million USD per vessel in 2012. They predict that these costs shall continue to increase as vessel complexity increases. Reducing investment while meeting availability and reliability requirements has been an area of interest since WWII (Smith, 1989). However, subsequent research in this area has not affected this increasing trend.

Maintenance scheduling conducted using current methods cannot meet these requirements without significant financial and resource investment. Current methods consist of periodic Preventative Maintenance (PM) and the Reliability Centered Maintenance (RCM) framework. Periodic PM and condition-based PM may be utilized within the RCM framework. Over the past 50 years, periodic PM has allowed naval vessels to maintain an acceptable level of availability (Cordle, 2017), though may schedule excess maintenance activities due to rigid scheduling. RCM requires a dedicated maintenance team, in addition to resources required for periodic PM and condition-based PM performed within it Additionally, RCM prioritizes maintenance of equipment on lifecycle cost or risk bases. These can be difficult to estimate with limited data upfront, although all data driven maintenance approaches share this disadvantage. Maintenance decision making is guided using a decision diagram and is conducted manually by personnel, which introduces some uncertainty into maintenance decision making. The author has remarked that RCM should not be automated, however new maintenance methodologies should look to automated decision making for consistency and to increase workflow efficiency.

Thus, periodic PM and RCM are not strictly the most optimal methods to perform maintenance scheduling and contribute to increasing

* Corresponding author.
E-mail addresses: Jane.cullum@utas.edu.au (J. Cullum), jonathan.binns@utas.edu.au (J. Binns), michael.lonsdale@serco-ap.com (M. Lonsdale), rouzbeh.abbassi@utas.edu.au (R. Abbassi), vikram.garaniya@utas.edu.au (V. Garaniya).

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maintenance costs of naval vessels.

Therefore, maintenance approaches and frameworks successful in other industries should be investigated for application to ships, and in particular complex naval vessels, to improve upon existing methods. An applicable framework is Risk-Based Maintenance (RBM) Scheduling, which has been implemented in other industries such as power generation. This paper aims to contribute to the development of improved maintenance scheduling for naval ships by reviewing existing applications of the RBM Scheduling framework; evaluating it against existing periodic PM and RCM frameworks; considering key activities in its implementation and developing this framework for application to ships and to naval vessels specifically. Naval vessels are the focus of the present work due to their aforementioned availability requirements and the significant financial investment in their maintenance. However, the present work is also applicable to the maintenance of ships in general.

Section 2 describes the current maintenance environment for naval vessels. Section 3 presents the concept of RBM Scheduling and existing applications of this framework to naval vessels and ships. Section 4 lists objectives, considerations and requirements to direct the future development of applications within this framework, and evaluates RBM Scheduling against periodic PM and RCM. Section 5 outlines processes for the implementation of the RBM Scheduling framework for organizations currently using the periodic PM approach within no framework or within the RCM framework. Section 6 presents a structured approach for the development of applications within RBM Scheduling. Section 7 suggests suitable methods to quantify the success of this framework in a given application. Section 8 presents a formalization of this framework for RBM Scheduling, and Section 9 summarizes the key findings and recommendations of this paper.

2. Maintenance of naval vessels

2.1. Current maintenance practice

Numerous methods exist to identify and schedule maintenance activities. These can be described as reactive maintenance, Preventative Maintenance and predictive maintenance. Reactive maintenance allows a failure to occur before an action is taken. This is not desirable in a naval application due to the potential consequences of the loss of an asset on the mission, safety of personnel and the organization's reputation. Preventative and predictive maintenance approaches aim to conduct maintenance in order to prevent failure, so are more suited to this application. Predictive maintenance is an attractive approach as future maintenance and inventory requirements can be anticipated, but to date it has not been applied in the naval industry. Current practice for naval vessels consists of maintenance actions scheduled at uniform intervals which are guided by Original Equipment Manufacturer (OEM) recommendations, previously described as periodic PM. Otherwise, maintenance scheduling is performed using the judgment of experts within the organization (Eruguz et al., 2015). When available, historical failure data may also be utilized where the organization adopts the RCM framework (Moubray, 1997). Adopting RCM requires additional resources to capture and analyze failure data and perform reliability modelling.

2.1.1. Preventative Maintenance (PM)

PM approaches can be further subdivided into periodic and condition-based approaches. Periodic PM actions are scheduled at uniform intervals based on some estimated equipment age, operating hours or another relevant measure according to OEM recommendations. Periodic PM assumes that failures are most likely to occur near the end of these uniform intervals. Periodic PM also assumes that a single estimated age or number of operating hours are an accurate indication of equipment condition, which may not be realistic. This is due to the influence of other factors such as the operational profile of the equipment. Periodic PM is favorable from a management perspective, as maintenance planning will only be conducted once per component or system using OEM guidance. Future maintenance and resource requirements are assumed to be uniform and predictable.

Periodic PM cannot accurately adapt to the current condition of the equipment, and therefore does not strictly perform maintenance when it is necessary. Assuming that the OEM directs increased maintenance to avoid premature failure, maintenance actions may be performed when they are not necessary. This results in increased costs and reduces the availability of the equipment. Additional factors such as human error in performing the maintenance task, or the "burn in" period of a new part may also contribute to a further reduction in availability (Moubray, 1997). Furthermore, these additional factors may result in broader corrective maintenance actions. Thus, while periodic PM appears favorable from a management perspective, these additional factors require careful consideration for effective periodic PM management.

Condition-based PM actions are scheduled at non-uniform intervals, utilizing an assessment of the condition of the equipment. This may be completed by specialist condition-monitoring (CM) instrumentation and expertise or appropriately trained personnel. This approach is not as favorable from a management perspective. Firstly, specialist instrumentation introduces additional initial cost and requires technical expertise to install, operate and analyze condition data. Secondly, 'appropriate training' necessary to identify required maintenance introduces some subjectivity and uncertainty into maintenance scheduling and scheduling of equipment down time. However, knowledge of equipment condition and therefore the necessity of maintenance, avoids the aforementioned additional factors such as human error which may be introduced in a periodic PM approach.

2.1.2. Reliability Centered Maintenance (RCM) framework

The Reliability Centered Maintenance (RCM) framework was developed for the aviation industry as a means of ensuring asset availability and reliability (Potter et al., 2015). RCM ranks the maintenance of equipment by considering failure rates. Reactive, corrective, Preventative and predictive maintenance approaches can be utilized within this framework. A comprehensive treatment of RCM is provided by Moubray (1997). This treatment highlights that the preliminary work required of an organization, and ongoing maintenance management support to schedule maintenance within the RCM framework, is extensive and therefore costly. However, RCM has been implemented in a variety of applications such as with mining machinery (Hoseinie et al., 2016), railway joints (Ruijters et al., 2016), medical devices (Ridgway et al., 2016), and aircraft indicators (Guo et al., 2016). Further, RCM is recommended as a maintenance framework and an overall asset management strategy for energy, power and transportation sectors (Seow et al., 2016). Despite its applicability and the potential benefits of this approach, it is likely that failure data requirements and the extensive implementation and use of organizational resources have hindered the adoption of the RCM framework aboard naval vessels.

2.2. Factors affecting development of naval maintenance practice

There are numerous explanations for the lack of innovation in this field. Shorten (2013) identified that a lack of development beyond compliant periodic PM is mainly due to the absence of a significant motivating factor to drive change within the industry. Penalties and safety risks provide this motivation in the offshore oil and gas and nuclear industries. Cordle (2017) highlighted the difficulty in training personnel toward mastery of the current naval periodic PM system, which may contribute to the ongoing struggle with managing maintenance workload and costs using this approach. Innovation would require prior mastery of the existing approach. Eruguz et al. (2015) highlighted that innovation requires greater organizational collaboration between all parties including OEMs, regulatory reviews which facilitate change, and the development of predictive approaches. Additionally, has identified that implementing specialist monitoring equipment for condition based PM aboard vessels has its own specific challenges. Other barriers preventing the development and adoption of new maintenance strategies may include inconclusive evidence of their financial benefits and lack of access to naval ships to perform pilot applications.

As organizational factors preventing change are considered the most significant, obtaining organizational and naval support is necessary to begin changing the maintenance environment in the naval industry. Subsequent consideration can then be given to developing an appropriate framework and its applications for ships.

3. Development of risk-based maintenance (RBM) scheduling for naval platforms

3.1. RBM Scheduling concept

Given the limitations of periodic PM and RCM, it is worthwhile investigating maintenance frameworks that have been successful in other industries. An emerging framework is RBM Scheduling. The RBM Scheduling framework was developed for the power generation industry (Chen and Toyoda, 1989; Ochiai et al., 2005) as a means of reducing maintenance costs, while ensuring asset availability. RBM Scheduling aims to schedule maintenance dynamically using risk as a trigger. RBM Scheduling consists of two elements; Risk Assessment, followed by Maintenance Scheduling (Arunraj and Maiti, 2007). RBM Scheduling has been implemented successfully in industries such as aviation (Ahmadi et al., 2010; Kumar et al., 1999; Papakostas et al., 2010) and power generation (Khan and Haddara, 2004; Krishnasamy et al., 2005; Yatomi et al., 2004). An extensive review of the development of RBM Scheduling in various industries, in addition to applicable models and techniques used in applications within the framework is provided by Arunraj and Maiti (2007).

3.2. RBM Scheduling for naval vessels and ships

While the idea of RBM Scheduling for ships is not new, and has been accepted in principle by maritime regulatory bodies (Shorten, 2013), to date the adoption of RBM Scheduling for naval vessels has not been a large area of research. Only one recent study with an application to the maritime domain (Diamantoulaki and Angelides, 2013) included 'RBM Scheduling' in its title. However, the application of this framework is a moored floating breakwater, not a ship. Limited literature suggested that a more thorough search was required, which motivated the development of the present paper. RBM Scheduling studies were likely to be concealed behind other terminology and acronyms as this framework is not yet well defined. Relevant terminology included: Condition-based Maintenance (CBM), Integrated Vehicle Health Management (IVHM), Maintenance Management, Maintenance Program Design, Predictive Maintenance (PdM), Prognostics and Health Management (PHM), Prognostics and Vehicle Health Management (PVHM), Reliability, Reliability Centered Maintenance (RCM), Risk, Risk Management and Risk Analysis.

3.2.1. Existing studies and related work

Using the definition of the RBM Scheduling framework provided by Arunraj and Maiti (2007); eight studies (Baliwangi et al., 2006; Diamantoulaki and Angelides, 2013; Dinovitzer et al., 1997; Dong and Frangopol, 2015; Giorgio et al., 2015; Handani et al., 2011; Klein Woud et al., 1997; Smith, 1989) may be classified as RBM for ships. None of these studies acknowledge that they fit the definition of RBM Scheduling and while their content overlapped, they did not cite one another.

Related RCM studies exist with ship applications (Lazakis (2011); Lazakis et al., 2010; Turan et al., 2011; Wabakken, 2015) although they cannot be considered RBM Scheduling as they do not strictly schedule maintenance based on risk. Therefore, consistent terminology and critical analysis of the eight existing RBM studies is required to develop an RBM Scheduling framework for application to ship maintenance.

3.2.2. Techniques used in existing studies

Initial studies using RBM Scheduling focused on quantifying risk using risk indices and scheduling maintenance using expert judgment for individual pieces of equipment (Dinovitzer et al., 1997; Klein Woud et al., 1997; Smith, 1989). More recent methodologies generally utilized probabilistic approaches to quantify risk and optimization approaches to schedule maintenance, with a continued focus on individual pieces of equipment (Diamantoulaki and Angelides, 2013; Dong and Frangopol, 2015; Giorgio et al., 2015; Handani et al., 2011). These methodologies specifically that risk is a time-dependent property and often incorporated a detailed treatment of maintenance costs, though Giorgio et al. (2015) did not specifically schedule maintenance activities.

In one of these recent studies (Dong and Frangopol, 2015), maintenance scheduling is performed using multi-objective optimization. The optimization aimed to determine the time interval of inspection and repair for each structural detail during the time period of investigation by minimizing inspection costs, repair costs and an annual risk value. The optimization was performed using the following inputs: ship configuration; ship operational scenarios; corrosion scenarios; fatigue crack propagation; time-variant reliability index; construction cost of the structure; the inspection method; repair criterion; inspection and repair costs; the time period of investigation and the maximum number of inspections during this period. The constraints applied were: a specified range for the time interval between consecutive inspections; a minimum structural performance value; and a maximum total cost for both inspection and repair. The optimization resulted in a Pareto front, comprising multiple maintenance plans which would vary in maintenance cost and risk. The appropriate maintenance plan was to be selected using expert judgment. The techniques used in both Risk Assessment and Maintenance Scheduling for the existing RBM Scheduling methodologies are indicated in Table 1.

3.2.3. Limitations of existing RBM studies

Some of the present methods are limited to their specific applications due to their assumptions (Diamantoulaki and Angelides, 2013; Dong and Frangopol, 2015). The method proposed by Handani et al. (2011) is also limited if failures are not random. However, the model of random failure may be replaced with other reliability models as numerous alternatives exist (Ebeling, 2004). Other methods (Giorgio et al., 2015; Handani et al., 2011), may be generalized as their assumptions are not as restrictive. Use of these methods assume data can be obtained in order to perform the required analysis. These methods require further development so that they may be widely applied to different pieces of marine equipment.

3.2.4. Evaluation of risk assessment techniques – risk indices and probabilistic techniques

3.2.4.1. Risk indices. The assignment of a risk index to a given piece of equipment is achieved by considering the probability and likelihood of a

Table 1
Existing studies and their approaches to Risk Assessment and Maintenance Scheduling.

Reference	Risk Assessment Technique		Maintenance Scheduling Technique	
	Risk Index	Probabilistic Approach	Expert Judgment	Optimization
Smith (1989)	X		X	
Dinovitzer et al. (1997)	X		X	
Klein Woud et al. (1997)	X		X	
Baliwangi et al. (2006)		X		X
Handani et al. (2011)		X	X	
Diamantoulaki and Angelides (2013)		X	X	
Dong and Frangopol (2015)		X		X
Giorgio et al. (2015)		X		

failure, and reading a suitable value from an appropriate table of risk index values. This approach was used in three of the existing RBM Scheduling studies (Dinovitzer et al., 1997; Klein Woud et al., 1997; Smith, 1989). Though this approach is simple and time-efficient, the assigned value is affected by the assessments performed to create the risk index table, and the experience of the risk assessors. Risk indices may be accurate if they are re-assessed periodically and personnel are appropriately trained.

3.2.4.2. Probabilistic techniques. A probabilistic technique involves modelling the failure behavior of the equipment using a probability distribution in order to produce a probability of failure for the calculation of risk. Probabilistic techniques have been used in most of the existing RBM Scheduling studies (Baliwangi et al., 2006; Diamantoulaki and Angelides, 2013; Dong and Frangopol, 2015; Giorgio et al., 2015; Handani et al., 2011).

Probabilistic techniques are based on a thorough consideration of the failure behavior of the equipment. Thus, they are expected to produce a more accurate result than the assignment of a risk index value. Probabilistic approaches can also be utilized dynamically by repeating the analysis at appropriate intervals. The length of these intervals will vary based on the application. Although they require greater effort in their implementation, quantitative risk assessment techniques including probabilistic techniques should be applied when practical (Arunraj and Maiti, 2007). Quantitative techniques yield risk assessments which are consistent and easily interpreted.

Development and application of a probabilistic technique in risk assessment for naval vessel maintenance would provide an accurate, consistent and easily interpreted assessment based on knowledge of failure processes occurring in the equipment. The corresponding maintenance schedule would be expected to reduce the amount of maintenance, maximizing the reliability and availability of the equipment. As high reliability and availability are crucial in naval vessel applications, the development of such a technique is worthwhile.

However, probabilistic techniques rely on the availability of failure data, and are not as straightforward as assigning a risk index. These limitations may be overcome if required data is made available through appropriate simulations or experimental work, and further if the approach is developed into user-friendly software. It is also suggested that the probabilistic analysis be refreshed periodically as new data become available and that collaboration between multiple organizations within the industry is necessary to obtain comprehensive failure datasets. RBM Scheduling applications in other industries have utilized probabilistic approaches despite these limitations (Abbassi et al., 2016; Bhandari et al., 2016; Dawotola, 2012; Xu et al., 2013). Therefore, probabilistic approaches may be developed to inform the maintenance scheduling of naval vessels and ships.

3.2.4.3. General analysis and directions for risk assessment. In addition to their own advantages and disadvantages, none of the existing methods applied for risk assessment consider degradation states other than a binary state of failure or no failure. The inclusion of multiple degraded states is required to develop multiple definitions of failure in operation and a more accurate understanding of the risk of failure. Considering existing techniques, it is worthwhile utilizing a probabilistic technique to obtain a greater understanding of failure behavior. It is also worthwhile to develop a probabilistic approach which considers multiple modes of degradation.

3.2.5. Evaluation of maintenance scheduling techniques – expert judgment and optimization

3.2.5.1. Expert judgment. Expert judgment is used for the scheduling of maintenance activities. It is performed by appropriately trained personnel, based on their experience. Expert judgment is used in most of the existing RBM Scheduling studies (Diamantoulaki and Angelides, 2013; Dinovitzer et al., 1997; Handani et al., 2011; Klein Woud et al., 1997; Smith, 1989).

The relevant personal experience of experts in scheduling the maintenance of complex systems in the absence of probabilistic data results in a reasonably efficient maintenance schedule. However, some uncertainty is introduced as this experience is individual, cannot be measured and continues to evolve over time. An additional limitation is that this technique is time consuming. The expert must assess all of the equipment, operational profiles of vessels and an unknown number of other factors based on their experience. A system which captures this experience and these factors would assist in clarifying for others the maintenance scheduling process used by one expert, and would assist the same expert to schedule maintenance more efficiently.

3.2.5.2. Optimization. Optimization techniques treated maintenance scheduling as an optimization problem. This is the minimization of a cost function describing the problem, to select an appropriate maintenance interval. Two existing RBM studies employed optimization, minimizing the cost function using an iterative approach. Baliwangi et al. (2006) optimized the life-cycle cost of maintenance for a generic shipboard component to minimize the risk of failure and life-cycle cost over a given time period. Dong and Frangopol (2015) optimized inspection and repair times of ship structural details to minimize inspection costs, repair costs and risk. Numerous other optimization techniques exist and may be applicable to the maintenance scheduling problem. A general overview of optimization algorithms is provided by Venter (2010).

The key advantages of optimization over expert judgment are consistency and efficiency. Although, optimization is only effective if it can capture all of the factors influencing maintenance scheduling as constraints or as part of the cost function. Fixed constraints mean that the possible range of solutions found using an optimization approach does not evolve over time, unlike the experienced decision making of an expert. Optimization may be applicable if relevant factors could be captured as constraints or within the cost function, provided that these are reviewed periodically.

3.2.5.3. General analysis and directions for maintenance scheduling. As multiple states of degradation were not considered, none of the existing techniques suggested specific maintenance actions for the application. In a pump application, this may be 'grease bearing' if the bearing was identified to be operating inefficiently. Suggesting a specific maintenance action for the application is necessary as there is no reasonable action defined as simply 'perform maintenance', 'repair' or 'service' in actuality. Different actions treat different conditions occurring in the equipment.

Reflecting on the previous discussion, it is worth investigating either optimization or expert judgment, or a combination of these to overcome their respective limitations. A suitable decision rule is required for multi-objective optimization approaches to suggest a specific maintenance action. Appropriate techniques from other fields and applications are also applicable to the problem of maintenance scheduling.

4. Developing an RBM Scheduling framework

4.1. Objectives for the development of an RBM Scheduling framework

To address the limitations of existing techniques as discussed in Section 3, methods should be developed within the RBM Scheduling framework to achieve the following objectives.

In Risk Assessment: Identify when maintenance is needed by quantifying risks of failure using a probabilistic approach, and quantify the risks of all failure modes occurring within a piece of equipment.

In Maintenance Scheduling: Schedule maintenance actions only when maintenance is needed, using the outcomes of the Risk Assessment, and utilize a suitable technique to select a single maintenance action, considering the outcomes of the Risk Assessment.

While not strictly necessary for the development of the RBM Scheduling framework, applications should also consider: vessel mobility (Eruguz et al., 2015) affecting both the operational environment of the on-board systems; the supply of resources to the vessel; vessel motion; the marine environment; alignment of the schedule to an existing maintenance cycle for the ship; and the capability of the vessel's crew to conduct maintenance at sea and the operational profile of the vessel (Usage Upkeep Cycle). These factors should be captured in the risk assessment technique or combination of techniques. The operational profile and the supply of resources to the vessel should be considered in scheduling maintenance.

4.2. Requirements for RBM Scheduling as a maintenance framework

RBM Scheduling is a maintenance scheduling framework similar to RCM. Therefore, RBM Scheduling should be treated as a maintenance framework to guide applications as has been presented in this paper, rather than a specific method of performing maintenance. RBM Scheduling applications require dedicated personnel who understand how to schedule the maintenance of individual equipment based on risk as well as prioritize high-risk maintenance within a system application. Dedicated personnel are required to design applications as well as manage ongoing implementations of RBM. Allocation of dedicated personnel will ensure that investment made in implementing this framework delivers the greatest return. Although it is a distinct framework, RBM Scheduling may be implemented exclusively or in combination with other frameworks such as RCM as most appropriate to the organization.

The concept of RBM Scheduling is very similar to the Reliability and Criticality - Based Maintenance (RCBM) framework developed for ship applications by Lazakis et al. (2010). RCBM uses an assigned 'criticality' akin to a risk index to schedule maintenance. As such, RBM Scheduling should also meet the following requirements which were defined by these authors for RCBM. The requirements are grouped into those relating to Methodology and Implementation and Data Management.

Methodology and Implementation: An RBM methodology should have a clear structure; incorporate flexibility; involve feedback from operational procedure; be subject to periodic reviews; allow for a quantifiable measure of the performance of the methodology; include training material and include an operator interface which makes use of pictures, videos and technical drawings.

Data Management: An RBM methodology should incorporate or interface with a Computerized Maintenance Management System (CMMS); incorporate a data storage and analysis system and allow stakeholder access to relevant data.

Section 8 describes how RBM Scheduling addresses each of these requirements.

4.3. Evaluation against periodic PM and RCM

If the previous objectives, considerations and requirements are included within the RBM Scheduling framework, numerous advantages and disadvantages will be evident with respect to periodic PM under no maintenance framework and RCM. These are summarized in Table 2.

Table 2 shows that the key advantage of adopting an RBM Scheduling framework is a reduction in maintenance cost and corresponding improvement in availability, while the key disadvantage is the organizational effort and resources required to implement the strategy.

Thus, in preference to periodic PM and RCM, the adoption of RBM Scheduling should be pursued to achieve a reduction in maintenance costs and ensure availability of the application. Consideration must also be given to implementation requirements of RBM in comparison to periodic PM or RCM. These are presented in Section 5.

4.4. Risk assessment using probabilistic techniques

Section 3 highlighted that a probabilistic technique should be developed further to perform the risk assessment within the RBM Scheduling framework.

4.4.1. Condition monitoring using probabilistic data

Probabilistic techniques require specific data as part of the Risk Assessment element of RBM Scheduling. While historical data is commonly used, collection and analysis of condition monitoring (CM) data has also been identified as a useful approach in some of the existing RBM studies (Baliwangi et al., 2006; Diamantoulaki and Angelides, 2013; Smith, 1989). This is distinct from condition-based PM approach described in Section 2. Various techniques exist to generate CM data, perform signal processing and the subsequent data analysis. The appropriate measurements are identified and techniques are selected with reference to the application. Some of these measurements and signal processing techniques relating to rotary machinery have been discussed in a general review by Lee et al. (2014).

CM data can be analyzed using signal processing and data analysis techniques to detect faults in equipment. Existing applications include bearings (Abbasion et al., 2007; Kankar et al., 2011; Samanta et al., 2006; Sharma et al., 2015; Sugumaran et al., 2007; Widodo et al., 2009) and gearboxes (Chen et al., 2013; Li et al., 2011, 2013; Staszewski et al., 1997). The combination of CM data, signal processing and data analysis is also known as fault detection or fault diagnosis. Further maintenance scheduling is not considered as a part of fault detection or diagnosis.

Machine learning techniques may be applied to perform data analysis. Machine learning techniques are applied to build mathematical models which make predictions based on their input data. A history of fault diagnosis using machine learning techniques is presented by Gao et al. (2015).

The fault diagnosis process aligns with the objective of the Risk Assessment element of the RBM Scheduling framework as both aim to assess the condition of equipment. Therefore, CM data and machine learning techniques may be directly incorporated into an RBM Scheduling framework.

4.5. Maintenance scheduling using a Decision Theory approach

The knowledge of experts with regard to maintenance scheduling is

Table 2
Evaluation of RBM Scheduling against periodic PM and RCM.

	Advantages of RBM Scheduling	Disadvantages of RBM Scheduling
Periodic PM (No framework)	Lower cost/higher availability	Greater flexibility required in resource planning
	Fewer introduced failures	Significant organizational change required
	Knowledge of failure processes and asset knowledge for improved asset and resource management	Potential greater initial financial investment required
RCM Framework	Lower cost/higher availability	Some further work required to implement framework
	Potential for automated, consistent decision making	Some organizational change required
	May still incorporate existing reliability considerations as failure probability can be deduced from reliability	Potential greater initial financial investment required
	More comprehensive treatment of failure if probabilistic approaches to risk assessment utilized	

critical and should not be disregarded. Expert judgment must be captured by the constraints or cost function in an optimization problem. Thus, it has been suggested that the combination of these techniques or a new technique should be employed to solve the scheduling problem. As part of the RBM Scheduling framework, optimal solutions must account for the risks of failure of the equipment due to various failure modes.

Decision Theory could prove beneficial. Applying this theory, it is possible to quantitatively capture the preferences of experts. A comprehensive development of Decision Theory is given in French (1986). Using the concept of utility, it is possible to model expert preferences to both select a single action to take and to create a ranked list of actions. While Decision Theory does not strictly allow for the calculation of a maintenance interval, it is possible to incorporate delays into a maintenance scheduling decision. Therefore, it is possible to create an effective decision making tool within an RBM Scheduling framework by using Decision Theory alone, or in combination with an existing optimization technique.

4.5.1. Related works: Decision Support for ships and naval vessels

Numerous studies exist with maritime applications which could be described as 'Decision Support'. Decision Support is the application of a decision tool to inform decision making, but not to ultimately select a single maintenance action. An example is the application of a Bayesian Network (BN) methodology to maritime safety management, in which the 'probability of safety system inadequacy' was determined by Hänninen et al. (2014). The study provided information to a decision maker to enable safety management decision making, though it utilized variables which could not be measured. Therefore, the model could not be validated. This study highlights the main limitation of Decision Support methodologies, despite their ability to provide some clarity and consistency in the decision process. Decision making methodologies are necessary to provide a single solution to the underlying problem.

4.5.2. Related works: decision making for ships and naval vessels

There are also numerous examples of decision making studies in the maritime context. Studies applying network-based models in Decision Support or decision making are largely concerned with navigation or vessel assignment problems (Eleye-Datubo et al., 2006; Liu and Yang, 2004; Perera et al., 2011; Yang et al., 2009). The Fuzzy Analytic Network Process (FANP) decision making methodology has been applied to the issue of shipyard location selection in Turkey (Guneri et al., 2009). Further examples exist apply the RCM framework for ships and naval vessels; such as the work of Lazakis and colleagues (Lazakis (2011); Lazakis et al., 2010; Turan et al., 2011) who adopted a Multi-Criteria Decision Making (MCDM) approach for ship maintenance scheduling. Recently, Emovon and colleagues have applied MCDM methods in order to select maintenance approaches (Emovon, 2016b; Emovon et al., 2015), conduct Failure Modes and Effects Analysis (Emovon, 2016a), and determine inspection intervals for marine machinery (Emovon et al., 2016).

These studies would suggest that currently available information in the maritime context can be used to support decisions, and specifically maintenance scheduling decisions. Thus, it is possible to develop a decision making tool within the RBM Scheduling framework for ship and naval vessel applications.

5. Implementation of an RBM Scheduling framework for SHIPS

Section 2 described how the periodic PM approach under no maintenance framework and the RCM framework are not optimal for ship applications. Section 4 suggested that costs to transition to the RBM Scheduling framework may be an additional barrier. To address this issue and provide clarity for the implementation of the RBM Scheduling framework for a given naval or ship application, key transition activities are outlined in the following sections.

5.1. Transition from no overall maintenance framework

Key activities forming a suggested transition approach of an organization to RBM Scheduling for a given application are presented in Fig. 1. This transition approach has been derived from the RCM framework for ships developed by Lazakis and colleagues (Lazakis (2011); Lazakis et al., 2010; Turan et al., 2011). This approach covers the minimum requirements for RBM Scheduling as a maintenance framework listed previously.

In the first phase of the implementation process shown in Fig. 1, establishment of a dedicated team for the ongoing management of applications is required. It is suggested that this team consist of vessel operations managers, Masters, Chief Engineers, other shipboard engineers, maintenance engineers, asset managers and vessel operators. Alternatively, these personnel may be involved separately as resources for the development of new applications. As maintenance scheduling using risk is a new concept in maintenance management for the given organization, a policy review or development is also required.

With the resources and structure in place, the scope of an application can be defined in the second phase of this approach. There are numerous information, data and interfacing requirements for the development of an application. Interfacing requirements may include integration of the RBM Scheduling data management and analysis system to update an asset management system with CM data, suggested maintenance tasks and maintenance intervals. Provided that the necessary information and data can be obtained, the scoped application may proceed. Otherwise, the scope of the application should be re-evaluated in this phase.

Design of the RBM Scheduling data management and analysis system and interfaces for the given application occurs in the third phase of the approach. Subsequently, an operational trial of the system and testing of the interfaces are necessary to confirm expected operation for the application. If experimental data were lacking from the previous phase, experiments to obtain this data are to be conducted in this phase. Recommendations made using the system should also be evaluated against the current maintenance approach to measure any improvements in availability and corresponding reductions in maintenance costs which result from its use.Section 7 presents quantitative means to achieve this.

Rework of the system or its interfaces may be necessary in the fourth phase of the approach to ensure acceptance of the final system design and system interface operation. In the final Integration phase of this approach, a user acceptance test is necessary to confirm that the system and organizational policies will combine to deliver improved maintenance schedules.

Following the Integration phase, it will also be necessary to periodically revalidate the system. It is suggested that this be completed if a significant change in operational profile occurs or following maintenance activities such as a vessel overhaul. The revalidation period should be assessed with respect to the application and adjusted accordingly.

5.2. Transition from RCM

The most significant organizational change required to transition from the RCM framework to the RBM Scheduling framework is the identification and acquisition of the RBM Scheduling management team in the Establishment phase. Due to their existing technical expertise, it would be reasonable to reassign reliability engineering personnel to the team. Otherwise, the key RBM Scheduling transition activities are shown in Fig. 1. As the organization will have existing maintenance management systems, a smoother transition is expected from RCM in comparison to periodic PM under no overall maintenance framework. Alternative approaches to a transition are to harmonize RCM and RBM as seen in other applications by combining risk and reliability (Selvik and Aven, 2011) or adding RCM into RBM (Liu Jr, 2013).

6. Development of RBM Scheduling applications

Although RBM Scheduling applications exist in other industries, few

I	ESTABLISHMENT	• Identify organizational resources for ongoing management of RBM Scheduling applications • Identify organizational resources for the development of new RBM Scheduling applications • Review existing or develop new organizational policy governing the use of RBM Scheduling Framework

II	APPLICATION DESIGN	• Identification of scope of RBM Scheduling application
		• RBM Scheduling development team to procure all relevant information for initial project planning, including:
		  ○ Operating profile of application
		  ○ Technical specifications and documentation
		  ○ Maintenance history of application
		  ○ List of causes of failure for the given application
		  ○ List of methods effective in measuring progression of application toward of causes of failure
		  ○ Experimental data describing occurrences of all causes of failure for the given application, under typical operating conditions
		• Identification of interfacing requirements with existing asset management systems

III	SYSTEM DESIGN AND VALIDATION	• Preliminary design of RBM Scheduling data management and analysis system - tailoring of Risk Assessment and Maintenance Scheduling techniques for the given application • Preliminary design of RBM Scheduling system interfaces with asset management systems • *Operational Trial:* Procurement of relevant condition monitoring equipment and acquisition of appropriate condition-monitoring data • [As required] Procurement of additional experimental equipment, and acquisition of appropriate experimental data • Testing of RBM Scheduling and asset management system interfaces • Evaluation of RBM Scheduling application recommendations against existing maintenance regime
IV	DESIGN ACCEPTANCE	• [As required] Rework of RBM Scheduling system design • Acceptance of final system design • Acceptance of system interface operation
V	INTEGRATION	• Personnel debrief and training • *User Acceptance Trial:* Operate condition monitoring equipment and RBM Scheduling system in alignment with organizational policy

Fig. 1. RBM Scheduling implementation approach.

applications for naval vessels have been developed to date. Section 2 highlighted that two of the contributing factors hindering the development of maintenance frameworks and applications in general were related to vessel access and organizational support in the naval industry. Although vessel operation and configuration is sensitive, access to naval vessels currently in service must be granted and support provided to obtain realistic maintenance data. These data are necessary to develop new maintenance approaches with the appropriate level of detail. An approach suggested in the present work is to develop RBM Scheduling applications beginning with individual pieces of equipment. Considering individual pieces of equipment also means that maintenance analyses may be completed without requiring comprehensive knowledge of all systems aboard the vessel.

Moving beyond individual pieces of equipment, it is suggested in the present work that there is a hierarchical relationship between the different types of applications in the naval industry. Fig. 2 illustrates that applications may be described as a hierarchy of four levels, from the application of a maintenance framework at the fleet level, to an application at the component level. ‘Component’ refers to a single unit of equipment, such as a pump or compressor.

Subsequently, RBM Scheduling applications for a sub-system, system, vessel and fleet can be developed according to Fig. 2. Potential effects on Risk Assessment and Maintenance Scheduling due to the connections between components should be investigated for higher-level applications such as sub systems.

The selection of the application is limited by the organizational resources available to develop and support the data collection and analysis. This is a key consideration in the implementation of the RBM Scheduling framework, described previously in Section 5. Investment of resources to conduct maintenance according to the RBM Scheduling framework is expected to be offset by the reduction in maintenance cost for the organization. It is expected that as applications for sub-systems, systems, vessels and fleets are developed, further reductions in maintenance costs shall continue to offset the resource requirements. The greatest maintenance cost reduction is expected when applying RBM Scheduling to a fleet of vessels, which should be the aim of an organization striving for optimal efficiency in maintenance management.

7. Quantifying effectiveness of RBM Scheduling

It is important to quantify the success of future RBM Scheduling applications to motivate further applications. Delivering the required availability of naval vessels in combination with a reduction in maintenance costs are the objectives of the framework and evidence of its success. Existing RBM Scheduling studies with ship or naval applications (Baliwangi et al., 2006; Diamantoulaki and Angelides, 2013; Dinovitzer et al., 1997; Dong and Frangopol, 2015; Giorgio et al., 2015; Handani et al., 2011; Klein Woud et al., 1997; Smith, 1989) did not consider availability as a measure of success, though maintenance costs were considered. Contrary to this trend, future applications should include quantitative means of measuring the improvement provided by RBM Scheduling on application availability and overall maintenance cost to provide evidence that RBM Scheduling is worthwhile. A suitable method of calculation of availability in terms of time may be selected from those presented in Ebeling (2004). Overall maintenance cost may be calculated as the total cost of tools, parts and labor necessary within a given time period. Labor cost may also include training or certifications required by the relevant personnel for the collection of CM data. Demonstrating and quantifying improved or sustained availability in combination with reduced overall maintenance cost in comparison to periodic PM shall motivate future RBM Scheduling applications within an organization.

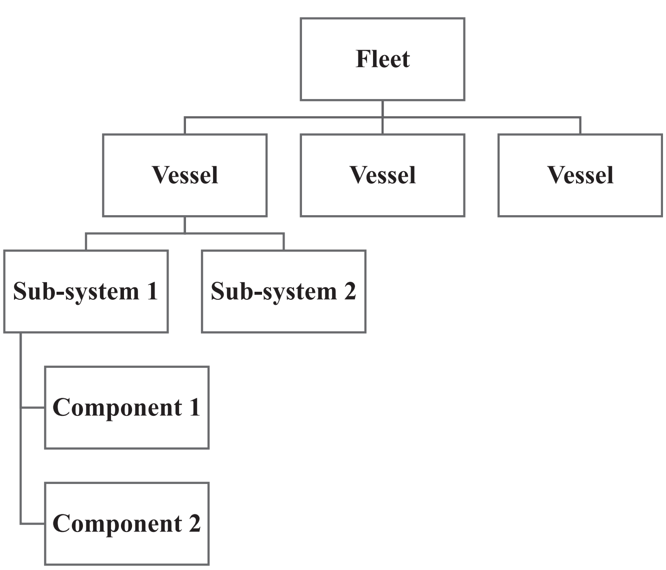

Fig. 2. Naval application hierarchy.

8. An RBM Scheduling framework

The development of the RBM Scheduling framework in Sections 3–7 against the objectives, considerations and requirements detailed in Section 2 is shown in Table 3.

The structure of the RBM Scheduling framework developed from the previous discussions requires continuous improvement as illustrated in Fig. 3.

The framework is cyclic as it is necessary to perform condition monitoring periodically. This ensures the risk assessment is current, and updates corresponding maintenance schedules. This is reflective of other RBM Scheduling applications within other fields (Mili et al., 2008). Maintenance Scheduling impacts both availability and overall maintenance cost. Further, adjustments to availability affect the risk assessment of the following cycle. Future RBM Scheduling applications should be

Table 3
RBM Scheduling framework requirements.

Requirement	RBM Scheduling Framework
Identify when maintenance is needed (risk of failure), considering all failure modes	Condition monitoring and definition of “failure”.
Dynamic maintenance scheduling based on risk of failure, selecting a single maintenance action	Decision Theory and possibly optimization.
Considering vessel mobility and operational profile	CM using experiments and data from targets of study aboard similar vessels or the specific target of study.
Clear structure	Two elements: Risk Assessment and Maintenance Scheduling. Calculations of availability and maintenance cost could be considered a third element.
Flexibility	Shown in feedback loops in implementation - Fig. 3. Techniques for CM and maintenance scheduling can be adjusted as required.
Feedback from operational procedure	Shown in CM data.
Periodic reviews	Mentioned as part of implementation, necessary for accurate Risk Assessment.
Quantifiable measure of performance of methodology	Availability and overall maintenance cost calculation
Incorporate computerized maintenance management system (CMMS)	Used as appropriate.
Data storage and analysis	Used as appropriate.
Stakeholder access to relevant data	Permitted and necessary for periodic reviews.
Training material	Can be developed for the application.
Operator interface	Can be developed for the application and organization.

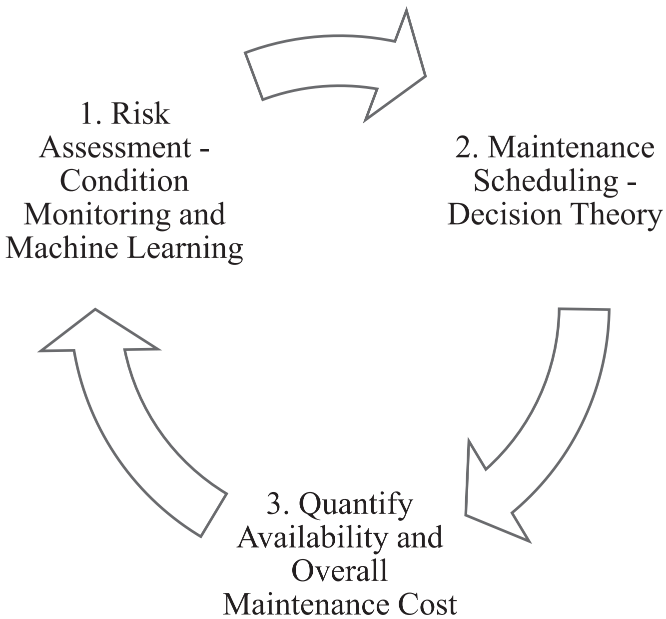

Fig. 3. RBM Scheduling framework.

developed within this framework to improve upon periodic PM and RCM used in existing naval vessel and ship applications.

9. Conclusions

The RBM Scheduling framework has been investigated to address the issue of rising expense in naval maintenance. Examination of the literature surrounding RBM Scheduling applications to ships and naval vessels has revealed that the use of this framework is limited and requires further development for these applications. In principle, the RBM Scheduling framework is capable of providing improvement when optimized for ship availability and maintenance cost. Avenues for future work include incorporating CM and machine learning techniques into the Risk Assessment element; as well as incorporating Decision Theory and optimization techniques for selection of specific maintenance actions in Maintenance Scheduling.

Key activities required in the transition from periodic PM or RCM to an RBM Scheduling framework incorporating these elements were presented, and were found to be more extensive than for periodic PM than RCM. It is suggested that multiple component level methodologies are developed initially, and subsequently integrated into sub-system, system, and vessel and fleet level applications. The level of application is limited by organizational resources. Quantifying improvement provided by RBM Scheduling over existing maintenance practice was suggested using metrics of availability and overall maintenance cost. Specific training of personnel to obtain CM data should be considered as part of overall maintenance cost. Lastly, the overall framework for RBM Scheduling was illustrated as a cyclic process comprising Risk Assessment, Maintenance Scheduling and quantification elements. Sufficient resources are required from appropriate organizations in the maritime industry or navy in order to collect data, and develop suitable Risk Assessment and Maintenance Scheduling criteria for future applications of RBM Scheduling. An RBM Scheduling framework appropriately developed for ships and naval vessel applications is expected to deliver maximum availability while minimizing overall maintenance cost.

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